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Temperature emerging of combination frequencies in quasi-2D Shubnikov–de Haas effect

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Abstract. The theory of the Shubnikov–de Haas effect is presented for quasi-2D systems when several subbands of size quantization are occupied. The temperature behavior of oscillation spectrum is considered. It is shown that the main harmonics with frequencies defined by subband fillings damp exponentially and the non-damping oscillations with differential frequencies proportional to energy gaps between subbands manifest themselves. They are harmonics, which became dominating at the following increasing of temperature.

It is known that the Shubnikov–de Haas effect displaying in the conductivity oscillations under quantized magnetic fields is caused by consequently crossing of the Fermi level by Landau subbands. The period of oscillations is found proportional to the carrier concentration what allows to use this phenomenon for its determination. Temperature increasing leads to broadening of carrier distribution and to suppression of the conductivity oscillations.

The qualitatively new situation takes place in two-dimensional (2D) structures where two or more subbands of size quantization are occupied. In this case, the oscillations appear with several frequencies determined by filling of subbands. It is important that the harmonics corresponding to the excited subbands exist even at relatively small degree of their filling due to intersubband scattering. Besides, the oscillations with frequencies proportional to energy gaps between size-quantized levels may appear in quasi-2D systems. The peculiarity of these harmonics is that they do not damp with temperature increasing [1].

The aim of this communication is the theoretical consideration of the magnetoconductivity temperature behavior in the presence of intensive intersubband scattering. We investigate an electron gas in 2D structure with two occupied subbands. Scattering is assumed to be isotropic and a spin spilitting in a magnetic field is neglected.

In 2D systems, the Shubnikov de Haas oscillations are observed in fields $\omega_c\tau \leq 1$, where ω_c is the cyclotron frequency and τ is the momentum relaxation time determined by both intra- and intersubband scattering. To calculate the conductivity tensor, it is convenient to use the Green function formalism. The main and the combine frequencies appear in the first and second order in the parameter $\exp(-\pi/\omega_c\tau)$ respectively.

The Green function of quasitwodimensional electron gas at finite temperature in the Matsubara technique has in energy representation the form

$$\mathcal{G}_j(\epsilon_m, \xi_{j,n}) = [i\epsilon_m - \xi_{j,n} - \mathcal{X}_j(\epsilon_m)]^{-1} \tag{1}$$

where $\epsilon_m = \pi T(2m+1)$, T is the temperature in energy units, m is a whole number, $\xi_{j,n} = \hbar\omega_c(n+1/2) - \mu_j$ is the energy distance between the n-th Landau level in the j-th subband and the chemical potential level. The self-energy parts, $\mathcal{X}_j(\epsilon_m)$, are found from the system of integral Dyson equations and has the following form in the second order in

$\exp(-\pi/\omega_c\tau)$:

$$\mathcal{X}_j(\epsilon_m) = -\sum_{j'=1}^{M} \frac{i\hbar}{2\tau_{jj'}} \left\{1 + 2\exp\left(-\frac{\pi}{\omega_c\tau_{j'}}\right) \exp\left[2\pi i \left(\frac{\mu_{j'}}{\hbar\omega_c} - \frac{1}{2}\right) \operatorname{sign} m\right] \right.$$
$$\times \exp\left(-\frac{2\pi|\epsilon_m|}{\hbar\omega_c}\right) + \left(1 - \frac{2\pi}{\omega_c\tau_{j'}}\right) 2\exp\left(-\frac{2\pi}{\omega_c\tau_{j'}}\right)$$
$$\left. \times \exp\left[4\pi i \left(\frac{\mu_{j'}}{\hbar\omega_c} - \frac{1}{2}\right) \operatorname{sign} m\right] \exp\left(-\frac{4\pi|\epsilon_m|}{\hbar\omega_c}\right)\right\} \operatorname{sign} m\,. \quad (2)$$

Here τ_{jj} and $\tau_{jj'}$ are the times of intra- and intersubband scattering in the zero magnetic field, and τ_j is the total scattering time in the jth subband.

Calculating the polarization operator with help of (1), one can obtain the expression for the conductivity tensor. At zero temperature, the main contribution appears from the first order in $\exp(-\pi/\omega_c\tau)$ terms [2]. The terms of higher orders are small and therefore are not observable. However, at raising of temperature, the amplitudes of the main harmonics decrease exponentially and the non-damping with temperature oscillations of higher orders may manifest themselves. In the second order in $\exp(-\pi/\omega_c\tau)$, the former have the form

$$\sigma_{xx}^{(nd)} = \sum_{j=1}^{M} \frac{N_j e^2 \tau_j/m}{[1 + (\omega_c\tau_j)^2]^2} \left[\frac{2\tau_j}{\tau_{jj}} - 1 + (\omega_c\tau_1)^2 \left(1 - \frac{6\tau_j}{\tau_{jj}}\right)\right]$$
$$\times \sum_{j'\neq j} \frac{\tau_j}{\tau_{jj'}} 2\cos\left(2\pi \frac{\mu_j - \mu_{j'}}{\omega_c}\right) \exp\left[-\frac{\pi}{\omega_c}\left(\frac{1}{\tau_j} + \frac{1}{\tau_{j'}}\right)\right] \quad (3)$$

$$\sigma_{xy}^{(nd)} = -\sum_{j=1}^{M} \omega_c\tau_j \frac{N_j e^2 \tau_j/m}{1 + (\omega_c\tau_j)^2} \left\{1 + \frac{2\tau_j}{\tau_{jj}} \frac{3 - (\omega_c\tau_j)^2}{[1 + (\omega_c\tau_j)^2]^2}\right\}$$
$$\times \sum_{j'\neq j} \frac{\tau_j}{\tau_{jj'}} 2\cos\left(2\pi \frac{\mu_j - \mu_{j'}}{\omega_c}\right) \exp\left[-\frac{\pi}{\omega_c}\left(\frac{1}{\tau_j} + \frac{1}{\tau_{j'}}\right)\right] \quad (4)$$

where m is the carrier effective mass and N_j are the concentrations in subbands. At further increasing of temperature, these oscillations dominate.

In Figure 1 the dependences of the resistance, ρ_{xx},

$$\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \quad (5)$$

on magnetic field are presented for the structure with two occupied levels of size quantization. The components σ_{xx} and σ_{xy} include the terms of zeroth, first and temperature-non-damping second order in the parameter $\exp(-\pi/\omega_c\tau)$. At calculation we assumed that the carrier concentration in the excited subband is relatively small, $N_2/N_1 = 0.1$, intersubband scattering is intensive, $\tau_1 = \tau_2$, $\tau_1/\tau_{12} = 0.5$, and the condition of good conductor is executed in both subbands: $\mu_1\tau_1/\hbar = 50$, $\mu_2\tau_2/\hbar = 5$.

Figure 1(a) corresponds to the case of zero temperature. The oscillations from both subbands are clear. The low-frequency harmonic exists due to intensive intersubband scattering.

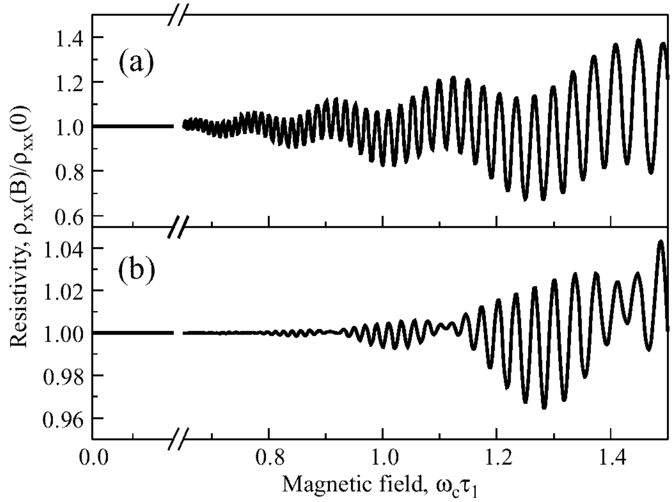

Fig. 1. Magnetoresistance oscillations in the presence of intensive intersubband scattering at different temperatures. (a) $T = 0$, (b) $T = 2T_D$.

In Figure 1(b) the case of $T = 2T_D$ is presented, where $T_D = \hbar/2\pi\tau_1$ is the Dingle temperature. The amplitudes of the main and differential harmonics are comparable, and therefore the beats are observable because the differential frequency is close to the main one due to the small filling of the excited subband.

In conclusion, the effect of temperature emerging of combine frequencies in the quasi-2D Shubnikov–de Haas effect is described consequently in the communication.

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